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Comparison between experimental and theoretical angular distributions of some proton groups from $B^{10}(d,p)B^{11}$ and $O^{18}(d,p)O^{19}$

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With 6 figures in the text

Introduction

Angular distributions of proton groups from $B^{10}(d,p)B^{11}$ and $O^{18}(d,p)O^{19}$ at a deuteron energy of 0.800 MeV were given in [1] and [2] respectively. The groups correspond to the levels 6.758 ± 0.007, 6.808 ± 0.007 and 7.298 ± 0.006 MeV in B^{11} [3] and to the ground state and 0.096 ± 0.008 MeV level in O^{19} [4]. In the present paper an angular distribution of the group leading to the 7.987 ± 0.014 MeV level in B^{11} [5] is given, measured at the same deuteron energy as in [1, 2]. A distribution of this group has not been reported before. Furthermore, theoretical curves have been calculated for the six proton groups using the deuteron stripping theories of Butler [6] and Bhatia *et al.* [7] and a comparison is made.

In [6] and [7] some effects are neglected, e.g. the one caused by Coulomb interaction. In spite of this, it has been observed in many cases that the theories give a rather good agreement with experimental distributions, although the deuteron energy is low. This is seen, for instance, for some other groups from $B^{10}(d,p)B^{11}$ [8]. Therefore, it seems valuable to make a comparison with these simple theories for the present groups. Of course it would be interesting to take e.g. the Coulomb interaction into account [9, 10], but then the numerical calculations are cumbersome. However, it follows from such calculations that a fair agreement of non-Coulomb theory with experiment is possible for light nuclei, if the interaction radii are suitably chosen.

A difficulty with (d,p) angular distributions especially at low deuteron energies is the isotropic part which is often of important magnitude. This part is generally assumed to depend essentially on compound nucleus formation and is subtracted before the curve is compared with stripping theory. The method is somewhat unsatisfactory and makes the evaluation less certain. However, it is not possible for the present to take a compound nucleus contribution into account in another way. The method is therefore used in this paper.

Angular distribution of the group from $B^{10}(d,p)B^{11}$ to the 7.99 MeV level

The same experimental procedure was used as in [1]. The target, consisting of 10 μg/cm² enriched B^{10} on a 2 μ Au-backing plated on Cu, was the same one as was used for the 7.30 MeV group [1]. The deuteron exposure was about 1000 μC for each angle. For θ_{lab} greater than about 120° it was difficult to separate the boron group from contamination of another group (probably $O^{16}(d,p)O^{17}$, $Q_1 = 1.046$ MeV). The measuring points are shown in Fig. 4, where also the statistical deviations are indicated. θ is the centre of mass angle. The distribution has a broad maximum at about 75°.

A function fitted to the experimental points was evaluated in a series of Legendre polynomials of the first kind. Being normalised to unity for $\theta = 90°$, it has the form:

$$I(\theta) = 0.82 + 0.14\,P_1 - 0.37\,P_2 - 0.11\,P_3 + 0.07\,P_5.$$

Terms, small compared to the experimental uncertainty for all angles, were excluded. The function has not been drawn in Fig. 1 to avoid making that figure indistinct.

Discussion

The measured and calculated distributions are compared in Figs. 1–6.

As mentioned above, a suitably large isotropic background has first been subtracted from the experimental points (except in Fig. 1). A best agreeing stripping curve corresponding to a fixed l_n value has then been determined by choosing the parameters r_0 of [6] and R of [7] respectively in a convenient way. Thereby the same deuteron wave-function as in [6] has been applied in both theories, and reduced masses have been used to allow for the finite target mass. The maximum of a curve has an angular position determined mainly by a certain l_n and less by reasonable variations in the values of the reaction radii. The background subtracted is probably not wholly due to compound nucleus formation, as it should also contain an appreciable contribution caused by the effects neglected in [6, 7].

$B^{10}(d,p)B^{11}$:

(*a*) The distribution of the 6.76 MeV group is seen in Fig. 1. Well fitting curves are obtained without a background for $r_0 = 5.6 \times 10^{-13}$ cm and $R = 6.9 \times 10^{-13}$ cm

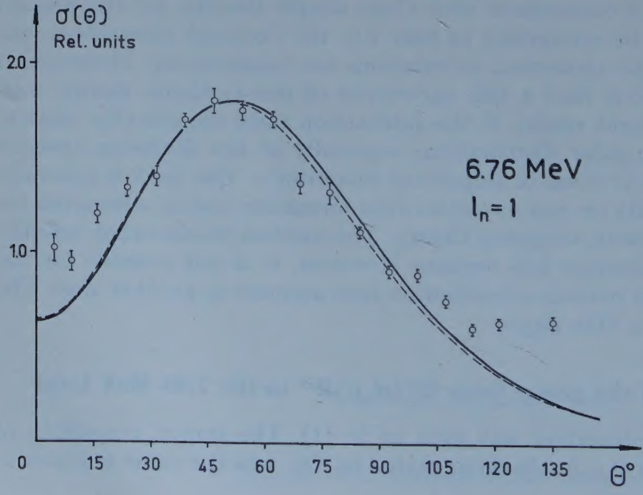

Fig. 1. Angular distribution of the $B^{10}(d,p)B^{11}$ group leading to the level 6.76 MeV of B^{11}. $E_d = 0.8$ MeV. $l_n = 1$. Solid line: Butler theory, $r_0 = 5.6 \times 10^{-13}$ cm. Broken line: Bhatia *et al.* theory, $R = 6.9 \times 10^{-13}$ cm.

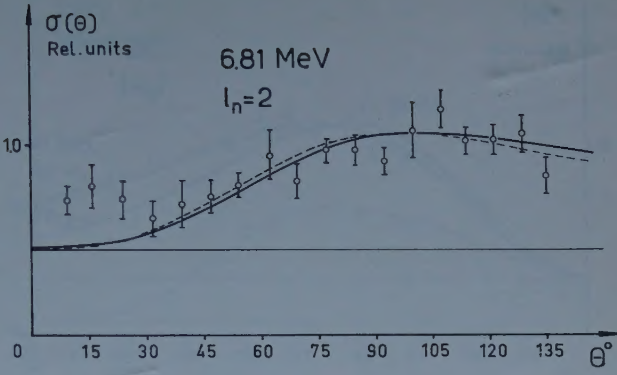

Fig. 2. Angular distribution of the $B^{10}(d,p)B^{11}$ group leading to the level 6.81 MeV of B^{11}. $E_d = 0.8$ MeV. $l_n = 2$. Solid line: Butler theory, $r_0 = 5.6 \times 10^{-13}$ cm. Broken line: Bhatia *et al.* theory, $R = 6.9 \times 10^{-13}$ cm. Fine line: isotropic background.

with $l_n = 1$. No other l_n values are possible—$l_n = 2$ e.g. gives a maximum at about 110°. It is noted that the radii are rather large. For $r_0 = 4.75 \times 10^{-13}$ cm, the Butler curve has its maximum at about 60°. The good consistency in Fig. 1 with the experimental points—the discrepancy at the smallest and greatest angles may depend on the Coulomb interaction—is remarkable and it seems to be quite certain that we have a stripping process with $l_n = 1$ in this case. That means that the level has negative parity and spin 3/2, 5/2, 7/2 or 9/2. In a recent paper [11] angular distributions of the 6.76 MeV group are given at $E_d = 2.50$, 3.00, 3.50 and 3.90 MeV. In that paper the group is not separated from the one to the 6.81 MeV level, but it is assumed that thereby only a small additional contribution to the cross-section results. (The same is true at $E_d = 0.8$ MeV as seen in [1].) The distributions in [11] are all very similar to the one in Fig. 1, with the difference, however, that the maxima are at somewhat smaller angles in [11]. This similarity over a rather wide range of deuteron energies is a strong support for the assumption that a stripping process is dominant.

(*b*) The distribution of the group to the 6.81 MeV level is seen in Fig. 2. A large background is subtracted. Stripping curves for $l_n = 2$ are shown which correspond to the same values of the radii as were used for the preceding group. No other l_n value shows a good fit—$l_n = 1$ and $l_n = 3$ give maxima at about 50° (as in Fig. 1) and 170°

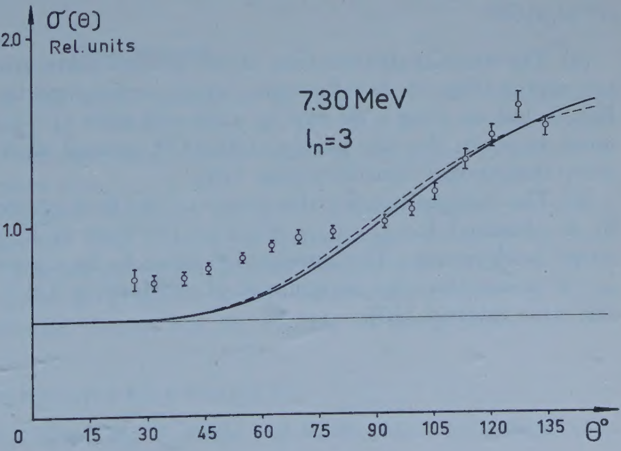

Fig. 3. Angular distribution of the $B^{10}(d,p)B^{11}$ group leading to the level 7.30 MeV of B^{11}. $E_d = 0.8$ MeV. $l_n = 3$. Solid line: Butler theory, $r_0 = 5.6 \times 10^{-13}$ cm. Broken line: Bhatia *et al.* theory, R = 6.9×10^{-13} cm. Fine line: isotropic background.

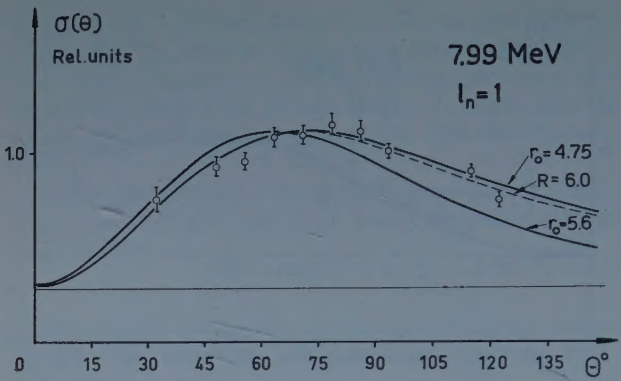

Fig. 4. Angular distribution of the $B^{10}(d,p)B^{11}$ group leading to the level 7.99 MeV of B^{11}. E_d = 0.8 MeV. $l_n = 1$. Solid lines: Butler theory, $r_0 = 4.75$ and 5.6×10^{-13} cm. Broken line: Bhatia *et al.* theory, $R = 6.0 \times 10^{-13}$ cm. Fine line: isotropic background.

respectively. The agreement might be an indication for stripping also in this case, even if it is less certain than for the 6.76 MeV group. $l_n = 2$ would mean positive parity for the level and a half-integral spin less than 11/2. From α-γ and γ-γ angular correlation measurements of the reaction $Li^7(\alpha,\gamma)B^{11}$, 3/2+ has been proposed [12].

(*c*) In Fig. 3 stripping curves with $l_n = 3$ plus a rather large isotropic background are shown for the next boron group (7.30 MeV). The same radii are used as in (*a*) and (*b*), and no smaller l_n is possible. If a deuteron stripping takes part in the reaction it would probably correspond to $l_n = 3$, which would mean negative parity of the 7.30 MeV level.

(*d*) As to the group to the 7.99 MeV state, the agreement between stripping curves and experimental points is not so good if the same radii are used as in (*a*), (*b*) and (*c*). However, $r_0 = 4.75 \times 10^{-13}$ cm and $R = 6.0 \times 10^{-13}$ give good agreement, if some background is assumed (Fig. 4). $l_n = 1$ is most probably the only possibility with reasonable values of the radii. The Butler curve corresponding to $l_n = 2$ and $r_0 = 5.6 \times 10^{-13}$ cm has a maximum at about 115°. Fig. 4 indicates that a deuteron stripping takes part in the reaction. $l_n = 1$ would mean negative parity of the 7.99 MeV level and a spin of 3/2, 5/2, 7/2 or 9/2.

$O^{18}(d,p)O^{19}$:

(*a*) The angular distribution of the ground state group disagrees with the theoretical curves (Fig. 5). $l_n = 2$ curves, which correspond to very large radii, are drawn in Fig. 5, but as good a fit can be achieved with $l_n = 1$ for smaller radii. However, l_n must be even for the parity of the O^{19} ground state to be positive which follows from shell-model considerations [13].

(*b*) The comparison for the group to the first excited state is interesting. A good fit is obtained for $l_n = 0$, $r_0 = 5.25 \times 10^{-13}$ cm or $R = 6.5 \times 10^{-13}$ cm and some isotropic background. The agreement seems to be a good support for $l_n = 0$ stripping. $l_n = 0$ means that the assignment of the level is 1/2+. That result might be of considerable interest [13].

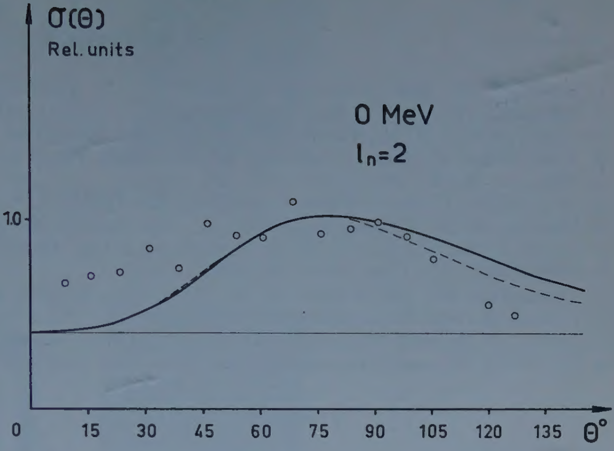

Fig. 5. Angular distribution of the $O^{18}(d,p)O^{19}$ group leading to the ground state of O^{19}. $E_d = 0.8$ MeV. $l_n = 2$. Solid line: Butler theory, $r_0 = 7.0 \times 10^{-13}$ cm. Broken line: Bhatia *et al.* theory, $R = 8.5 \times 10^{-13}$ cm. Fine line: isotropic background.

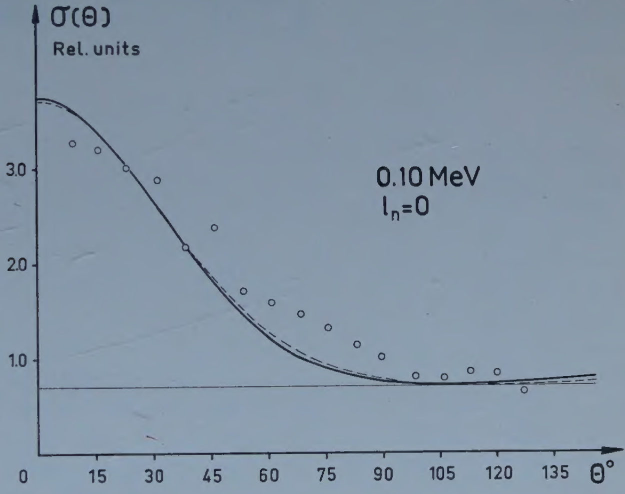

Fig. 6. Angular distribution of the $O^{18}(d,p)O^{19}$ group leading to the 0.096 MeV level of O^{19}. $l_n = 0$. Solid line: Butler theory, $r_0 = 5.25 \times 10^{-13}$ cm. Broken line: Bhatia *et al.* theory, $R = 6.5 \times 10^{-13}$ cm. Fine line: isotropic background.

Conclusions

The angular distribution of the boron group to the 6.76 MeV level shows that a deuteron stripping process with $l_n = 1$ takes place at $E_d = 0.8$ MeV. For the other boron groups the evidence is not so strong. However, it is tempting to believe in stripping processes in these cases too: $l_n = 2$ (6.81 MeV), $l_n = 3$ (7.30 MeV), $l_n = 1$ (7.99 MeV). Measurements at higher deuteron energies must be made before any definite conclusions can be drawn. This is still more true concerning the ground state group from $O^{18}(d,p)O^{19}$. For the group to the first excited state of O^{19} the indication of $l_n = 0$ stripping seems to be good. It would be of some interest to make a comparison with a more accurate theory, e.g. [9, 10], for all the groups.

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